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Characteristics and applications of varistors

by

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The Characteristics and Some Applications of Varistors*

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A study of editorial correspondence and verbal comments from readers of these PROCEEDINGS has shown that many of them desire the publication of tutorial papers on matters of current and major importance to the communications and electronic engineers. Such papers should be prepared by experienced and recognized workers in the corresponding field, and should be both clear and comprehensive. They should form a "refresher course" for the practicing engineer, and should be of further value as source material to active engineering workers and as advanced texts for the use of student members.

Accordingly the Board of Directors, upon recommendation of the Administrative Committee of the Board of Editors, has authorized the publication of such papers in the PROCEEDINGS. These papers are in each case procured and approved by the Subcommittee on Tutorial Papers, under the Chairmanship of Professor Ernst Weber, of the IRE Education Committee, under the Chairmanship of Professor H. J. Reich.

The following paper is of the type here described and deals with one of the newer and valuable instrumentalities used in the branches of engineering served by the Institute.—*The Editor.*

Summary—Varistors, circuit elements whose resistance is a function of the voltage applied, represent one important commercial application of semiconductors. They may be divided into two classifications: nonsymmetrical and symmetrical varistors. The first classification includes both metallic rectifiers such as copper oxide, selenium, and copper sulfide, and point contact rectifiers such as silicon and germanium. The only commercial varistor of the symmetrical class is the silicon carbide varistor, although a symmetrical characteristic may be obtained by connecting two nonsymmetrical varistors in parallel with proper polarity.

Each varistor has its volt-ampere characteristic and at each point on this characteristic two different values of resistance may be defined, namely the dc resistance, defined as the ratio of voltage to current, and the dynamic or ac resistance, defined as the ratio of dE to dI . The former is important in problems dealing with steady-state dc or large-signal applications, while the latter is important when dealing with small applied signals.

Because of the state of the art, varistors as manufactured commercially are less uniform than many other circuit elements and required uniformity is often obtained by special selection. Economical use of these elements therefore requires the circuit engineer to recognize clearly which of the several properties are important in his ap-

plication and to specify special selection for only those properties and to the extent necessary for his application.

Other properties of varistors which may be of importance are capacitance, maximum inverse voltage, effect of temperature and frequency on any of the other characteristics, long and short time stability, and noise.

Of the many applications of varistors three are discussed which illustrate how different properties may be determining factors in different applications. In power rectifiers the limiting factors are those which may physically damage the unit, energy dissipated within the varistor, and inverse voltage across the varistor. As a result such items as ventilation, duty cycle, and the like, are important. In bridge- and ring-(lattice) type modulators the problem of protecting the varistor against physical breakdown is seldom present, but the limiting factor is the extraneous modulation products introduced into the circuit. It is therefore necessary to make detailed analyses of the spectrum of the sum and difference products involved. In the compandor (compressor plus expander), operating economies are obtained by a device which is dependent on the uniformity of the dynamic characteristic of the varistor in its forward direction. A selected bibliography is included.

INTRODUCTION ✓

WHILE THE rectifying properties of certain metallic sulfides were known as early as 1874, the first commercial application of semiconductors was probably the crystal detector used in radio telegraphy during the first portion of this century. With the advent of the vacuum tube the crystal detector was supplanted, only to be recently reinstated in an improved version as a detector for microwaves. In the meantime, the copper-oxide rectifier was introduced about 1925 as a power rectifier. About 1936 this same copper-oxide unit was introduced as a modulator in carrier telephone circuits. This application was so successful that the copper-oxide modulator (later supplemented by silicon and germanium modulators) soon became an

essential portion of the long-distance telephone plant. Although a selenium rectifier was described as early as 1883, the commercial selenium rectifier was slow to develop and was not introduced on a wide-spread commercial scale until after the copper-oxide rectifier. Because of its lighter weight, smaller bulk, and lower cost, the selenium rectifier has supplanted the copper-oxide rectifier in many, but by no means all, applications. Microwave development during the recent war was responsible for the silicon and germanium rectifiers which today have been used for a wide variety of functions, many not related to their original purposes.

Despite the wide diversity of origin and usage, these devices—the early crystal detector, the copper-oxide rectifier and modulator, the selenium rectifier and the silicon and germanium rectifiers—all are but applications of the same basic principle, nonsymmetrical conduction at the junction between a conductor and a semi-

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conductor, or between two differing semiconductors. With this idea in mind the term "varistor" was coined about 1934 and is now defined as "a two-terminal circuit element composed of an electronic semiconductor and suitable contacts, which has a markedly nonlinear volt-ampere characteristic."¹

While the varistor was the first, and is still from the production viewpoint, the largest application of semiconductors, it is not the only application. Other applications include the thermistor (circuit elements whose resistance varies with temperature), the transistor (the semiconductor amplifier), and various photoelectric devices. None of these later applications will be discussed in this paper, as each is important enough to warrant a separate treatment.

The commercial varistors of today may be divided into two mechanical classes—the area contact type, and the point contact type. The first classification includes copper-oxide, selenium, and copper-sulfide units, and also silicon carbide disks or rods (more familiar to some engineers by trade names such as "Thyrite"). Point contact devices include the silicon and germanium varistors. Basically, area and point contact varistors have similar properties, and frequently both may be used for the same application. It is therefore planned to discuss both of these types together, pointing out their similarities and in some cases their differences.

Besides these commercial types, there are a large number of materials also known to have similar properties, such as the natural crystals used in early crystal detectors and many chemical compounds, particularly oxides and sulfide. It is therefore quite possible that in the future additional commercial types of varistors may be made available to the circuit engineer.

Electrically all varistors, either of the area or the point contact type, may be divided into two classes—symmetrical and nonsymmetrical varistors. The only symmetrical varistors commercially available today are of silicon carbide, although a symmetrical characteristic can be obtained by properly connecting two nonsymmetrical varistors. In this paper it is proposed first to discuss the characteristics of nonsymmetrical varistors, reserving the discussion of the symmetrical type for a later section.

NONSYMMETRICAL VARISTORS

All nonsymmetrical varistors, be they of the area or point contact type, consist of three essential elements, a body of a semiconductor and two electrodes. One of these electrodes makes an intimate contact with the

semiconductor and this junction is ideally a purely ohmic connection. Between the second electrode and the semiconductor is a barrier layer which is capable of passing current easier in one direction than in another. The mechanism of this barrier layer is more fully treated in various articles on the theory of semiconductors.²

The direction of easy current flow through the barrier layer is dependent on the type of semiconductor in the varistor. Two basic types, designated as *P*-type material and *N*-type material, exist. For varistors using *P*-type material, the direction of easy flow is obtained by making the body of the semiconductor positive. For those using *N*-type material, it is obtained by making the body of the semiconductor negative. Of the present-day commercial varistors, all are made of *P*-type material except germanium varistors, which are made of *N*-type material.³ }✓

In point contact varistors the barrier layer is always located at the point contact, but in area type varistors the location of the barrier layer is not self-evident. To help avoid this confusion Figs. 10 through 14 show simplified cross sections of each of the commercial types of varistors with the direction of easy current flow indicated.

Before considering the properties of any type of varistor in detail it will be well to emphasize their nature. First, because of their nonlinear characteristic, varistors cannot be characterized by a single dimensional adjective as we do when we specify, for example, a 50-microfarad condenser or a 10-ohm resistor. Rather, a varistor must be specified by its properties at several points on its characteristics, such as the current at one volt in forward direction, the current at five volts in reverse direction, and so forth. In general, the current at one point bears little and in many cases no relation to the current at another point, so that it is essential that the characteristic desired be completely specified at all points.

Second, because of the nature of the manufacturing processes now employed, varistors are not inherently uniform. Nonsymmetrical varistors bearing the same manufacturer's designation often differ in forward current at the same voltage by as much as 4 to 1, while the reverse current sometimes differ by even greater ratios. Any better uniformity, at the present state of the art, is obtained largely by selection. Fortunately, in many applications a high degree of uniformity is not necessary, so that the expense of such selection can be eliminated. It is therefore quite important for the circuit engineer to understand which properties are critical in the particular application at hand, so that the most economical selection of units can be made. The practice recently initiated by one manufacturer of publishing not only

¹ Tentative definition of ASA C42 subcommittee on communication definitions. The qualification "composed of an electronic semiconductor" excludes such devices as the electrolytic rectifier, popular with the radio amateurs in the 1920's, and the electrolytic condenser. Electronic processes differ from electrolytic processes in that no polarization voltages are produced nor is there any chemical decomposition of any of the elements of the device. As a result, the life of an ideal varistor is theoretically infinite.

² See references (1) through (6) in the Bibliography.

³ It is well known that many semiconductors, particularly germanium and silicon, may exist in either the *N* type or the *P* type. Hence this statement must be restricted to commercial varistors, since it is sometimes possible to construct units in the laboratory which have the reverse direction of easy current flow.

average curves but also curves showing the limits between which 80 per cent of the units may be expected to be found is to be commended. The more widespread publication of such data will eliminate much confusion that has existed in the minds of engineers wishing to use varistors.

The most commonly published characteristic for a varistor is the relation between the voltage across the varistor and the current through it. Such a characteristic is shown in Fig. 1(a). In one direction a small impressed voltage causes a relatively large flow of current. This is the so-called forward direction or direction of easy current flow. The usual convention symbol for a nonsymmetrical varistor shown in the upper left-hand corner of Fig. 1(a) is arrow-shaped, with the arrow

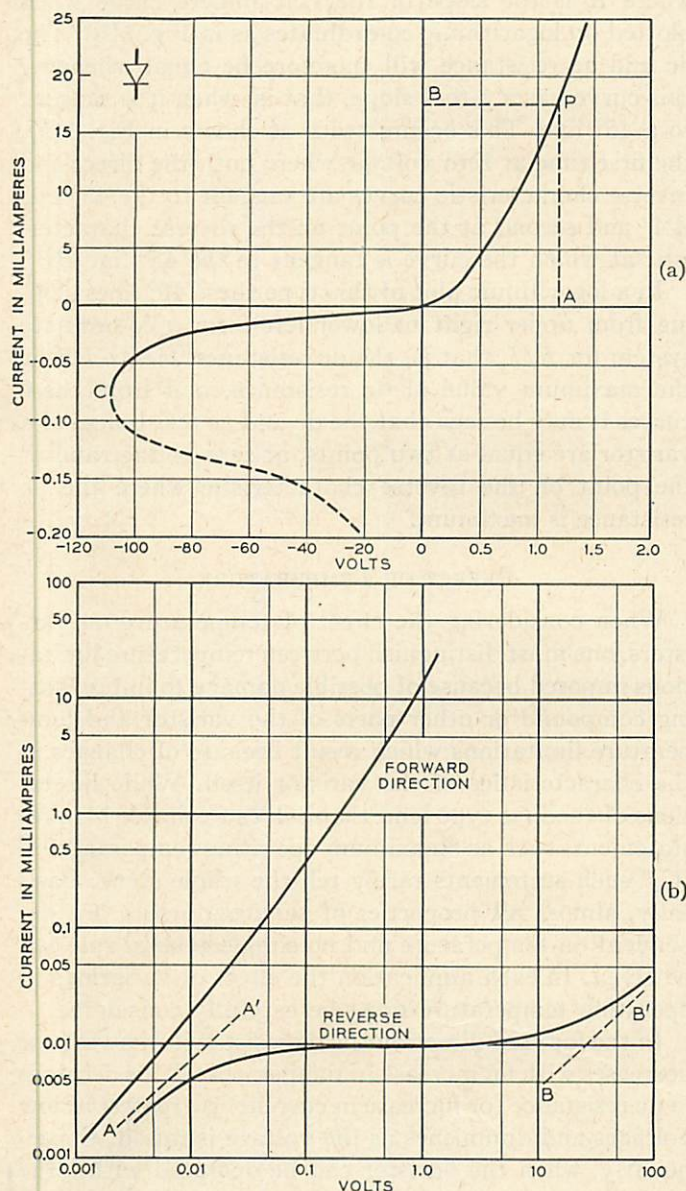


Fig. 1—Voltage-current characteristic of a typical nonsymmetrical varistor.

(a) Characteristic plotted using a linear scale. Note that the scale for the reverse portion of the characteristic differs from that of the forward portion.

(b) Characteristic plotted using a logarithmic scale.

pointing in the direction which current flows when operating on the forward portion of the characteristic.⁴

In the forward direction, this characteristic may be approximated by the empirical equation:⁵

$$I = AE^n \quad (1)$$

where I and E are the current and voltage, respectively, and A and n are empirical constants. The exponent n depends on the type of varistor and on the portion of the characteristic curve to which this empirical equation is fitted. For most varistors n is greater than 2, and in some cases may be as high as 4, or even higher. This is in contrast to the vacuum-tube diode, which has an exponent of the order of 3/2.

In all cases the characteristic curve passes through the origin. Unlike the vacuum-tube diode, there is no current at zero voltage due to contact potential.

In the reverse direction there is always a measurable current which increases as the reverse voltage is increased. In Fig. 1(a) both the voltage and current scales are different in the reverse direction. This is a quite common practice in plotting varistor characteristics and is generally necessary because of the large difference in magnitude between the forward and reverse currents.

When the reverse voltage reaches the point C , the reverse current increases very fast and in some varistors a region is reached where as the current is increased still further the voltage decreases. This negative resistance region⁶ is readily observed in germanium varistors. The voltage at point C is often designated as the "maximum inverse voltage" or "voltage for zero dynamic resistance." The exact value of this voltage is dependent on many factors, including ambient temperature and local heating produced during its measurement. Consequently its exact value is seldom specified but rather varistors are specified to have a "maximum inverse voltage" not less than a given value.

In types of varistors other than germanium the question of the existence of this maximum inverse voltage is of academic interest. With these varistors the reverse current becomes so great that the characteristic of the

⁴ The method of marking the forward direction on commercial varistors has not been standardized and some confusion exists because of the different points of view of the designs. For example, some germanium varistors have been marked with a "+" sign at the terminal corresponding to the upper end of the symbol in Fig. 1(a) to indicate that if the positive terminal of a battery is connected to this terminal current will flow in the forward direction. On the other hand, on some single-element selenium varistors the "+" designation is on the terminal corresponding to the lower end, because it is presumed that these units will be used as power rectifiers and hence this terminal will be the positive pole of the output.

⁵ The forward characteristic may also be approximated by other equations. One such equation of exponential form may be derived theoretically (see bibliography reference (1), chapter 4). However, these other equations are usually too cumbersome for ready engineering application.

⁶ While it is possible to operate germanium varistors in this negative resistance region in the laboratory, this portion of the curve is in general too unstable for commercial applications. Negative resistance regions have also been reported in the forward direction, but these regions are practically never found in normal operating ranges. It is interesting to note that W. H. Eccles is reported to have demonstrated an oscillator using a negative-resistance region in a galena crystal before the Physical Society of London in 1910.

varistor is permanently altered by internal heating before any negative resistance region is reached.

A varistor's characteristic inherently extends over a wide range of voltage and current, and so it is sometimes advantageous to plot this curve on a logarithmic scale. Fig. 1(b) shows the curve of Fig. 1(a) replotted, using logarithmic scales for both the voltage and current. Since in a plot of this type neither scale reaches zero, it is necessary to show different curves for the forward and reverse characteristics. As the scales are extended to the left to show smaller quantities, the forward and reverse characteristic curves both approach asymptotically the dotted line AA' shown in Fig. 1(b).

When dealing with a nonlinear device such as a varistor, one may define two different resistances and it is important when using the term "resistance" to specify which is referred to. The first is the ratio of voltage to the current at any point, such as the ratio OA/OB at the point P in Fig. 1(a). This frequently is referred to as the dc resistance and is of importance in problems involving the application of dc voltages to varistors.

In many applications the varistor is biased by a dc voltage, and a small ac voltage is superimposed on this dc bias. If we assume OA is such a bias, the ac voltage will see a resistance not of OA/OB but rather the reciprocal of the slope at the point P , that is, dE/dI . This resistance is called the dynamic or ac resistance. This dynamic resistance can be measured directly by a special bridge so arranged that the required dc bias can be superimposed on the varistor and the ac measuring voltage kept low, in the order of a few hundredths of a volt.

When a large ac voltage is applied to a varistor, the term resistance has no universal meaning. For a sinusoidal impressed voltage, the current wave is usually quite distorted and it is not possible to define resistance in terms of any simple ratio.

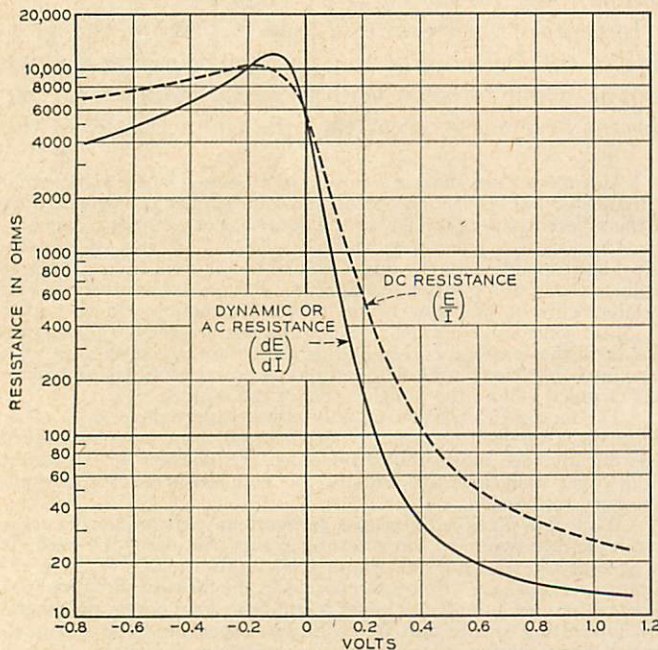


Fig. 2—Resistance-voltage characteristic of a silicon varistor.

Both the dc and the ac resistances are functions of the operating point. Fig. 2 shows the values of these two resistances for a silicon varistor plotted as a function of the dc voltage. At any point in the forward direction, the dc resistance is larger than the ac resistance, both resistances decreasing rapidly as the bias voltage increases. In the negative direction, both resistances reach a maximum, as in the case of the silicon varistor in Fig. 2 when the bias is only a fraction of a volt negative, and then decrease as the reverse voltage is increased.

The general relation between the dc and ac resistance is

$$R_{ac} = \frac{R_{dc}}{K} \quad (2)$$

where K is the slope of the volt-ampere curve when plotted on logarithmic co-ordinates as in Fig. 1(b). The dc and ac resistance will therefore be equal whenever this curve has a 1-to-1 slope, that is, when it is tangent to a 45° line. This occurs twice as shown in Fig. 1(b), the first time at zero voltage where both the direct and reverse characteristic curves are tangent to the 45° line AA' and second at the point on the reverse characteristic at which the curve is tangent to the 45° line BB' .

In a logarithmic plot of this type these 45° lines sloping from upper right to lower left form a co-ordinate system for E/I , that is, the dc resistance. Hence BB' is the maximum value of dc resistance, and from these curves it may be seen that the dc and ac resistances of a varistor are equal at two points, at zero voltage and at the point on the reverse characteristic where the dc resistance is maximum.

EFFECT OF TEMPERATURE

When considering the effect of temperature on varistors, one must distinguish between temperature limitations imposed because of possible damage to impregnating compound or other parts of the varistor and temperature limitations which result because of changes in the characteristics of the varistor itself. While limitations of the first type lend themselves to simple blanket statements such as "maximum operating temperature—°C," such statements rarely tell the whole story. Basically, almost all properties of semiconductors are dependent on temperature and no simple general rule can be given. In each application the effect of variations in operating temperature must be carefully considered.

In the forward direction the dc resistance of a varistor decreases with an increase in temperature. This decrease in dc resistance (or increase in current) is greatest at low voltages and diminishes as the voltage is raised. Consequently, when the varistor can be operated with large applied current, the effect of changes in operating temperature is minimized. At a given operating voltage, the temperature variation from unit to unit of the same type is relatively uniform.

In the reverse direction, as the temperature increases

the dc resistance also decreases (or current increases).⁷ This change is gradual at low temperatures, but as the temperature is increased a point is often reached at which the rate of change is greatly accelerated. At extremely high temperatures (in the order of 250°C) most varistors no longer act as rectifiers. Unfortunately, the allowable temperature for a given degradation in reverse characteristic is often not uniform with varistors of the same type.

The effect of temperature on the dynamic or ac resistance can be seen from the volt-ampere characteristic of a germanium varistor shown in Fig. 3. As the temperature increases the whole curve moves to the left. Except in the immediate vicinity of the origin, the curves tend to remain parallel to each other. Thus the change with temperature of the dynamic or ac is often less than the change in dc resistance. When dealing with dynamic resistance one must differentiate between the case in which operation is at constant bias voltage, as, for example, along line *AB*, and the case where the bias current is held constant, as along the line *CD* in Fig. 3.

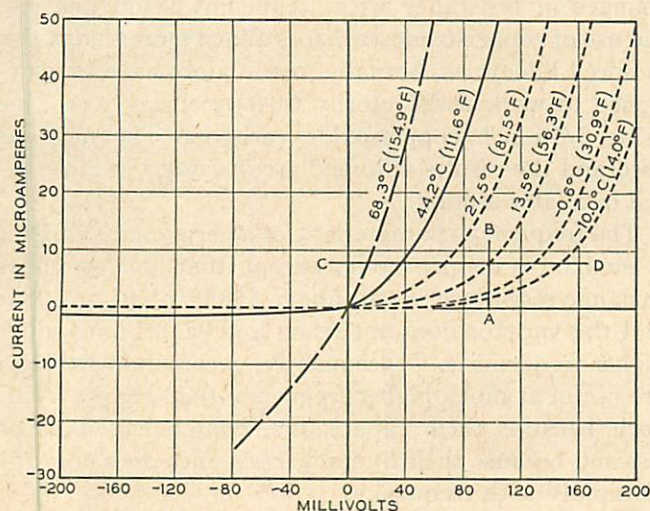


Fig. 3—Voltage-current characteristic of a germanium varistor in the vicinity of the origin showing the effect of changes in the ambient temperature.

Characteristics of a varistor are affected not only by changes in the ambient temperature but also by heat generated within the unit itself. This is illustrated by the oscillograms on a germanium varistor shown in Fig. 4. These oscillograms show the reverse half of the volt-ampere characteristic of the varistor and were taken after the varistor had been passing various amounts of forward current. The curve in Fig. 4(a) was taken before any forward current was applied. Fig. 4(b) was taken after application of 16 milliamperes in the forward direction. This current is well within the normal operating range of the varistor, and a comparison of Figs. 4(a)

⁷ Selenium is an exception to this statement. At lower temperatures the dc resistance decreases as the temperature decreases. The temperature for maximum dc resistance depends on the reverse voltage and lies in the range between freezing and usual indoor ambient temperatures. This temperature characteristic may depend on the processing of the unit, as published data from various sources are somewhat contradictory.

and 4(b) shows no appreciable change in the reverse characteristic. For Figs. 4(c) and 4(d), increasingly larger forward currents, well beyond the normal operating values, were applied before the oscillographs were taken. In Fig. 4(c) the increase in reverse current is noticeable. In Fig. 4(d) not only has the heating due to the previous forward current increased the reverse current, but it has also decreased the maximum reverse voltage.

In this test, when the unit was allowed to stand with no forward current for an appreciable length of time, the reverse characteristic returned to that shown in Fig. 4(a). In other similar tests in some cases such overloads have caused a permanent increase in the reverse current.

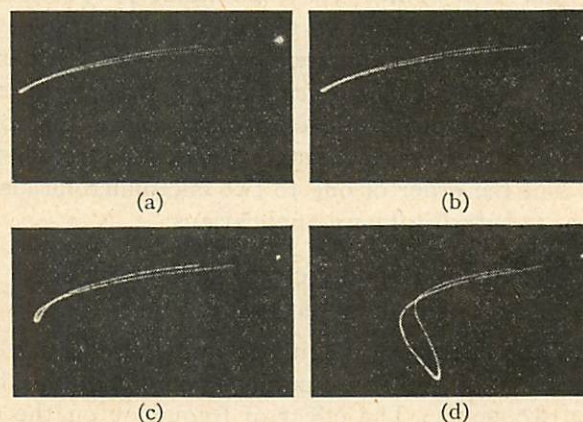


Fig. 4—Oscillograms showing the effect of heat produced by prior forward current on the reverse portion of the voltage-current characteristic of a germanium varistor.

CAPACITANCE

In any area-type varistor there is appreciable capacitance in parallel with the dynamic resistance. This capacitance is a function of the polarity and magnitude of the bias voltage and of the frequency. It may be measured using a bridge of the type described for measuring ac resistance. Fig. 5 shows the capacitance of a 3/16-inch copper-oxide varistor at both 10 and 200 kc.

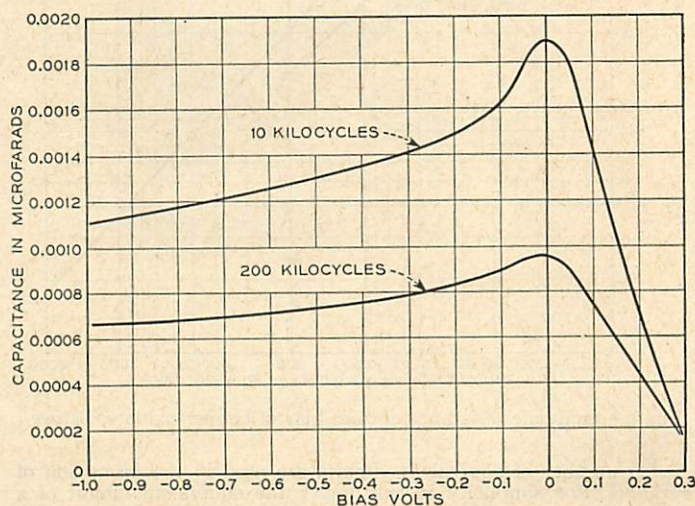


Fig. 5—Capacitance of a 3/16-inch copper-oxide varistor.

As the bias in the reverse direction is decreased the capacitance is increased, reaching a maximum at or near zero bias. As the bias is increased in the forward direction, the capacitance drops quite sharply, reaching a low value at high forward bias voltages.

At higher frequencies the curve has the same general shape, but the value of the capacitance is lower as shown by the curve for 200 kc in Fig. 5.

At large reverse bias voltage the capacitance of selenium is less than that of copper oxide, but as the bias voltage decreases, the rate of increase is larger in selenium than in copper-oxide varistors. As a result, at zero bias the capacitance of selenium varistors is larger than of copper-oxide varistors of the same area.

For point contact varistors it is probable that the capacitance acts in much the same manner, but measurements are more difficult to make because of the small magnitude of this capacitance, and because it is paralleled by a linear capacitance through the case of the same order of magnitude or greater. Since the total capacitance, barrier capacitance plus that through the case, is of the order of one to two micromicrofarads, it can be neglected in many applications.

EFFECT OF FREQUENCY ON IMPEDANCE OF VARISTORS

Both the effective capacitance and the effective resistance of a varistor⁸ are functions not only of bias, but also of frequency. The effect of frequency on the capacitance was as discussed in the preceding section. In general, as the frequency increases the resistance of a

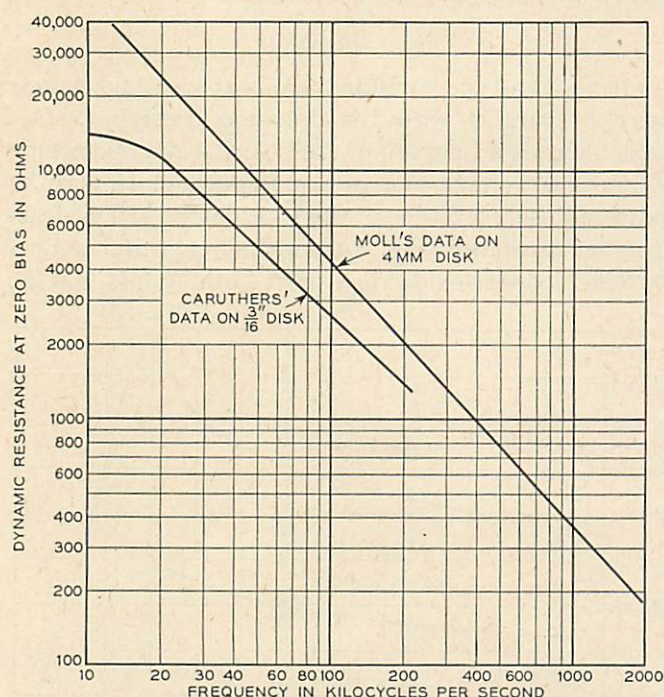


Fig. 6—Dynamic resistance at zero bias of copper-oxide varistors.

⁸ A number of equivalent circuits are used in the discussion of varistors. For simplicity in this paper the equivalent circuit of a varistor is considered as a resistance in parallel with a capacitance. Obviously all resistances in the section are dynamic or ac resistance.

varistor may be expected to decrease. Fig. 6 shows two sets of data taken on small copper-oxide varistors. Curve *A* is for 3/16-inch disks and is taken from Caruthers'⁹ paper on modulators, while curve *B* is for 4-mm disks and is taken from a similar paper published in France by P. Moll.¹⁰ Both curves show that for copper-oxide varistors the dynamic resistance decreases quite rapidly, with frequency falling from a value of over 10,000 ohms at low frequencies to a value of in the order of 200 ohms at 2 mc.

For negative bias the dynamic resistance is larger than at zero bias as shown in Fig. 2, and the curve of dynamic resistance versus frequency is approximately parallel to that at zero bias. At positive bias the dynamic resistance is much smaller, and as the value of resistance decreases, the variation with frequency decreases. Moll's article shows a curve for 4-mm copper-oxide varistor at +0.5 volts bias in which the dynamic resistance has a value of approximately 43 ohms for all values of frequency from 2 to 6 mc.

At first glance it would appear that these large changes in resistance with frequency would preclude the use of copper-oxide varistors above more than a few hundred kilocycles. Actually, modulators have been designed to work satisfactorily to frequencies over 2 mc using 3/16-inch copper-oxide varistors. The methods used and the results obtained are discussed in more detail in a later section.

The frequency characteristic of a germanium varistor is similar to copper oxide, except that the zero bias dynamic resistance is still above 10,000 ohms at 10 mc and the varistor does not reach low values until much higher frequencies. Consequently, germanium varistors are useful at much higher frequency than copper oxide, both because their capacitance component is much less and because their dynamic resistance does not drop as rapidly with frequency.

Silicon varistors in general have lower dynamic resistance than germanium, and, in contrast to germanium varistors, their resistance is almost constant for frequencies up to at least 50 mc. For this reason silicon varistors are well suited for broad-band applications.

STABILITY AND AGING OF VARISTORS

One major problem in the development of varistors has been the reduction of instability. Two particular types of instability are well known—gradual changes or aging in the characteristics of a unit over periods of months or even years, and short time drift or creep in the current during the first few minutes when potential is applied.

Aging in varistors is due to many causes, some of which appear at this time to be inherent in the varistor itself and some of which can be eliminated by changes in design or processing. In the former class are aging processes that take place within the body of the semi-

⁹ See bibliography reference (24).

¹⁰ P. Moll, *Cables et Trans.* (Paris), vol. 6, pp. 24-46; 1950.

conductor and the barrier layer. The mechanisms of these changes are as yet only partly understood. In the latter class are such causes as changes due to lack of mechanical stability of parts, deterioration of contacts, and the like. The efforts of all manufacturers to eliminate causes of these latter types have resulted in marked improvement in the stability of varistors since the first introduction of copper-oxide units about twenty-five years ago, and there are reasons to believe further improvements will be made in the future.

Aging in varistors in general results in a decrease in forward current (increase in forward dc resistance) and usually¹¹ an increase in reverse current (decrease in reverse dc resistance). The rate of these changes gradually decreases, and after a period of one or two years the rate of aging is only a fraction of the initial rate of change.

The magnitude of this aging usually increases both as the ambient temperature is increased and as the current through the varistor is increased. Since increased current causes increased internal heating, it is possible that the effect may be entirely due to temperatures. For large copper-oxide disks operating at their full rated current, the aged value of forward dc resistance (measured at constant current) may be as high as double the initial value.

The rate of change is often accelerated by increased ambient temperatures. For example, with copper-oxide varistors it has been found that ten days' storage at 60°C is roughly the equivalent of one year's storage at average room temperature. For applications which demand extreme stability, a pre-aging process of this type can sometimes be used to eliminate a large portion of the subsequent aging of the unit.

Two different approaches are used in the solution of the problem of aging. In power rectifiers, where aging may be expected to reduce the output of the rectifier as much as 20 per cent during its life, the circuit may be designed to operate satisfactorily at the reduced output, or taps may be provided on the transformer so that the applied voltage may be increased to compensate for aging. In the latter case the design of the unit must allow for the increased losses when the units are aged.¹²

In communication applications generally the amount of aging is less, as the varistors are usually operated at only a small fraction of their rated current. However, stability is much more important, particularly as it is desirable to reduce maintenance to a minimum. As a result of developments in production of varistors and careful circuit design, thousands of varistor modulators are today in operation in long-distance telephone circuits without any provision for routine maintenance tests. More detailed data on long time stability studies in communication circuits will be given in the sections

on application of varistors to modulators and comparators.

In addition to long time aging, investigators in the field of varistors sometimes, but not always, encounter a drift or creep in current during the first few minutes that potential is applied. This drift may occur in either the forward or reverse current, but it is more frequently observed when measuring reverse current. While this drift is quite annoying when attempting to measure the volt-ampere characteristic of a unit, it may go unnoticed in many applications, its effects being part of the warming-up period of apparatus.

Short time drift may be due to any one of a variety of causes. When operating at high reverse or high forward current, power losses within the varistor itself are sometimes sufficient to produce internal heating and thus change the varistor characteristic as it warms up. Drift of this type is inherent in the unit and cannot be avoided. Other types of drift may be due to faulty processing. For example, in at least one case drift in the reverse direction was traced to chemical deterioration in the impregnating compound used. Other cases probably involve mechanisms of conduction in semiconductors not yet fully understood.

NOISE

The fact that resistors have an inherent background noise due to thermal agitation (the so-called Johnson noise) is well known. Varistors also possess a background noise, but much less is known about the cause or nature of this noise. Unlike Johnson noise, which for a constant bandwidth is uniform throughout the frequency spectrum, varistor noise tends to vary inversely as the frequency. The noise in varistors probably is a function of the bias, appearing to be greater in absolute magnitude when biased in the reverse direction, although complete measurements are lacking. The comparison of the noise of different types of varistors is complicated by the problem of how the noise shall be expressed. The familiar designation "so many db above thermal noise" cannot be used in a circuit whose resistance (and hence theoretical thermal noise) varies with bias.

Noise becomes important when it is necessary to operate a modulator at very low levels. Field experience has shown that the quietest modulators are constructed with copper-oxide varistors.¹³ However, the data available are quite sketchy and it is by no means certain that this is the final answer.

OPERATION OF VARISTORS IN SERIES OR PARALLEL

When identical varistors are connected in series or parallel there is no particular problem. Random selected

¹¹ An exception is selenium varistors in which the reverse dc current frequently decreases during the first six months or so of their life.

¹² See bibliography reference (9)

¹³ Early copper-oxide modulators had a high noise level but with the development of these varistors, particularly with the improvement in their contacts, the noise level has been reduced to a low value.

varistors are seldom identical, which may introduce problems in parallel or series operation. Fig. 7 shows the reverse characteristic of two dissimilar varistors. If these two varistors are to be connected in series, a new volt-ampere characteristic can be drawn for the combination by noting that the same current always flows through each varistor, and that at any value of current the total voltage across the two units in series (that is the point on the new curve) must be the sum of the voltages at this current for each of the varistors. The two varistors in Fig. 7 have quite dissimilar reverse characteristics, and this figure illustrates the situation of an engineer who finds that for his application the reverse current at some voltage is too high. He adds a second varistor, hoping to cut the reverse current in half, but instead because of the dissimilar nature of the two varistors, the reverse current is only reduced by a very small amount. Hence the basic law, two random selected varistors will be no worse than a single varistor, but may be little better. For series varistors to approximately divide the reverse voltage, they must have approximately identical characteristics.

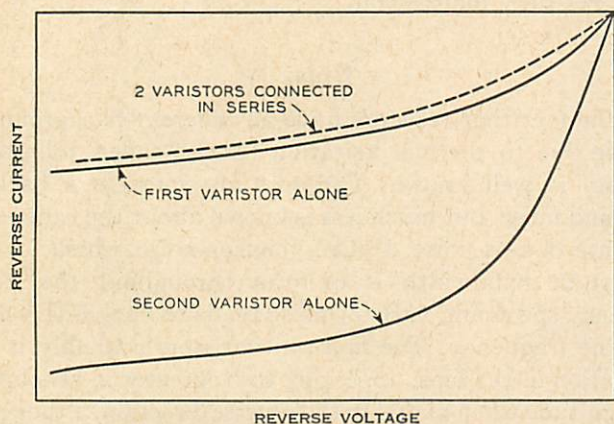


Fig. 7—Reverse portion of the voltage-current characteristic of two dissimilar varistors connected in series.

When varistors are connected in parallel, the same type of reasoning applies to the current. When varistors are connected in parallel, they divide the current equally only when they are identical.

THE SYMMETRICAL VARISTOR

The symmetrical varistor differs from the nonsymmetrical varistor in that the volt-ampere characteristic is the same in both directions as shown in Fig. 8. Essentially this characteristic can be obtained by connecting two identical nonsymmetrical varistors in parallel with the polarity as shown in Fig. 9. This connection suggests the convention symbol shown in the upper left corner of Fig. 8 for the symmetrical varistor.

Except for the absence of a high resistance reverse characteristic, symmetrical varistors are in many respects similar to nonsymmetrical varistors. Their ap-

plication at present is almost entirely confined to some type of protective circuit, such as lightning arrestors, click or thump reducers, and voltage limiters. In these applications the varistor presents a high impedance to the low voltages normally applied. The application of

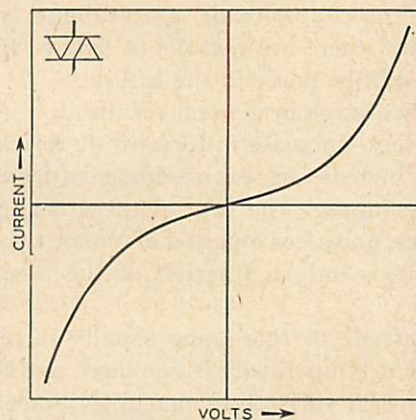


Fig. 8—Voltage-current characteristic of a typical symmetrical varistor.

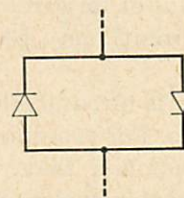


Fig. 9—Circuit connections for two nonsymmetrical varistors to obtain a symmetrical voltage-current characteristic.

abnormal higher voltages reduces the impedance of the varistor, thus limiting the amplitude of surge voltages.

CHARACTERISTICS OF COMMERCIAL VARISTORS

In this section, the general characteristics of various types of commercial varistors will be discussed and compared. While some data on units will be given, these figures are intended only to illustrate orders of magnitude, and are not intended as design data. For any application the necessary design data should be obtained from the manufacturer.

Copper-Oxide Varistors

Copper-oxide varistors are today manufactured in a wide variety of sizes, ranging from disks as small as 1/16 inch in diameter up to rectangular plates of at least 4 3/8 by 12 inches. The smaller units are used in meter rectifiers, modulators, and similar devices, while the larger plates are used for power rectifiers.

Basically these varistors consist of a copper plate on which a layer of cuprous oxide is produced by heat treatment. This cuprous oxide is the semiconductor and the barrier layer is located at the junction of the cuprous oxide and the mother copper (see Fig. 10(a)).

Contact to the cuprous oxide layer may be made in a variety of ways. In the early copper-oxide varistors this contact was made by a lead washer clamped under pressure against the face of the cuprous oxide. With this method of contact, the properties of the varistors are influenced to some extent by the pressure exerted on the lead washer. This type of contact is still used in units of the order of one to two inches in diameter, but has been generally superseded in smaller units and in the large copper-oxide plates.

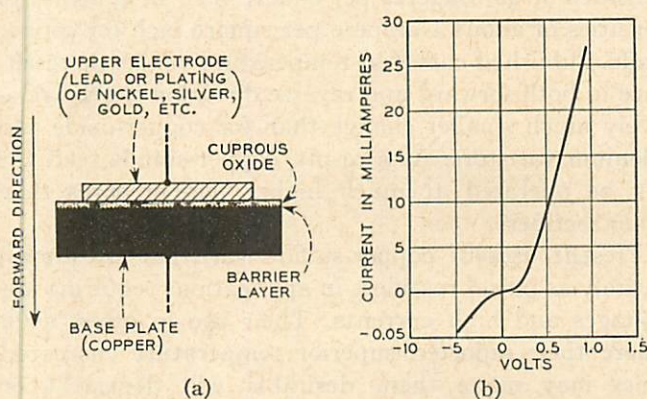


Fig. 10—Copper-oxide varistor.

In smaller varistors, contacts to the cuprous oxide layer is frequently made by evaporating a layer of silver or of gold on the oxide layer. This type of contact has been found to produce the greater degree of stability required for modulator and other nonpower applications. In large copper-oxide plates, contact is generally made by reducing the top surface of the cuprous oxide to metallic copper and then nickel-plating this surface.

The forward direction of current flow is from the top electrode to the cuprous oxide to the copper base, as shown by the arrow in Fig. 10(a). For a constant applied voltage the current in this direction is proportional to the area of the varistor. For a 3/16-inch disk the forward current at one volt is from 10 to 50 milliamperes, of the same order of magnitude as for silicon varistors and a little greater than for germanium varistors. Fig. 10(b) shows the volt-ampere characteristic of a 3/16-inch copper-oxide varistor.

In the reverse direction the current is proportional to the area with an added component, due to leakage around the periphery. This leakage component is generally minimized by careful control in manufacture. The reverse current does not show any negative resistance region. Continuous reverse voltage must be limited to the order of six volts¹⁴ to prevent damage to the unit, although copper-oxide varistors will withstand as much as 40 to 50 volts for infrequent transients. Both the reverse ac and dc resistance are moderately high, reach-

¹⁴ At least one manufacturer offers high reverse-voltage copper-oxide varistors rated at from 2 to 3 times this figure.

ing maximum values of the order of 100,000 ohms at a reverse voltage of a few volts for a 3/16-inch disk.

Most copper-oxide varistors are made using a copper base of high purity, but there are also available varistors whose base plate contains a small amount of thallium. In general, these varistors have higher dc and dynamic resistance at low-voltage levels and are used for special applications such as click reducers and other types of voltage limiters.

Selenium Varistors

As with copper oxide, selenium varistors are manufactured in a variety of sizes, ranging from disks one inch in diameter to large plates. Smaller size units are also available, but these have found much more limited application than small size copper-oxide units. Selenium varistors are made (see Fig. 11(a)) by depositing a layer of metallic selenium on a suitable base plate, generally of steel or aluminum. After suitable heat treatment, this selenium layer is covered by a layer of some low melting point alloy which forms the upper electrode. The melting point of the alloy frequently is one limitation in the operating temperature of selenium varistors.

In these varistors the semiconductor is the metallic selenium and the barrier layer is located between it and the top electrode. The forward direction of current is from the base electrode through the selenium to the top electrode, as shown by the arrow in Fig. 11(a).

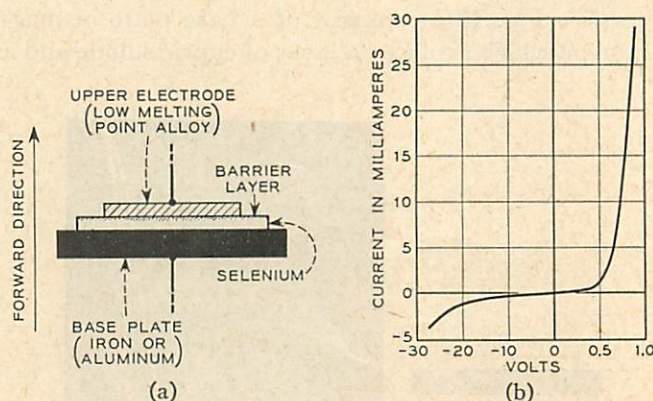


Fig. 11—Selenium varistor.

Fig. 11(b) shows the volt-ampere characteristic of a one-inch-square selenium varistor. For a given area at low forward voltages the forward current is less than for a copper-oxide varistor, as may be seen by comparing Fig. 10(b) for a 3/16-inch diameter copper-oxide varistor and Fig. 11(b) for a one-inch-square selenium varistor. These two figures also show the difference in the types of the forward characteristics. In copper-oxide varistors the forward current increases relatively fast as the forward voltage is raised, while in selenium varistors the first few tenths of a voltage cause very little increase in current.

In the reverse direction the characteristics of selenium varistors are less definite than copper-oxide, due to the tendency for the reverse characteristic to deteriorate when the varistor is standing idle. On the application of reverse voltage the unit is re-formed, generally within a few cycles or, at the most, a few seconds. This re-forming process is not objectionable in power applications, but limits the usefulness of selenium varistors in other fields.

The allowable reverse voltage for selenium varistors exceeds that of copper oxide. While copper-oxide units are generally rated in rectifier circuits at $4\frac{1}{2}$ volts applied ac per unit, at least two distinct types of selenium rectifiers are available with a rating of 22 and 33 volts applied ac per unit. This increased voltage rating reduces the number of varistors required in series, producing a lighter and cheaper rectifier.

Selenium varistors may be damaged by mercury vapor, and should not be used in any application where there is a possibility of such contamination.

In general, the use of selenium varistors is confined to power applications in which light weight, small bulk, and low cost are important, and in which stability with life and large overload capacity are of secondary importance.

Copper-Sulfide Varistors

As compared to copper oxide and selenium, the production of copper-sulfide varistors is quite small. These units are also produced in a variety of sizes ranging from disks $19/32$ inch in diameter to large plates. These varistors (see Fig. 12(a)) consist of a base plate of magnesium on which is placed a layer of cupric sulfide and a

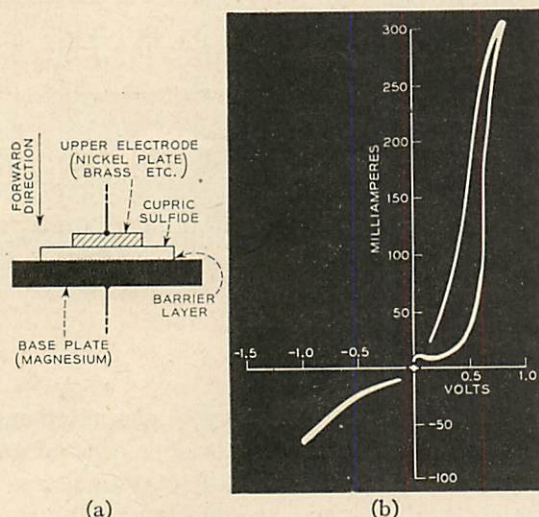


Fig. 12—Copper-sulfide varistor.

top electrode. The cupric sulfide is the semiconductor and the barrier layer is located between this sulfide and the magnesium base. Forward direction of current is from the top electrode through the cupric sulfide to the magnesium base, as shown by the arrow in Fig. 12(a).

Only a limited amount of information has been pub-

lished on the volt-ampere characteristics of copper-sulfide varistors, but it is generally reported that the forward current frequently is different for increasing and decreasing voltage as shown in the oscillogram in Fig. 12(b). In the reverse direction the current is much higher than that of either copper-oxide or selenium varistors, and the reverse voltage is quite limited. The two outstanding characteristics of copper-sulfide varistors are the current density at which they may be operated and their temperature characteristics. One authority reports that these units may be operated at current densities of 35 amperes per square inch in contrast to densities of about 1 ampere per square inch for copper oxide. Published curves of temperature versus dc resistance in both forward and reverse direction show a relatively much smaller change than for copper-oxide and selenium varistors. As a result, copper-sulfide rectifiers can be operated at much higher temperatures than other rectifiers.

Present uses of copper-sulfide varistors are almost entirely as power rectifiers in applications requiring low voltages and high currents. Their use in other fields where their reported superior temperature characteristics may make them desirable will depend upon whether greater stability of their volt-ampere characteristic can be obtained.

Silicon Varistors

The use of silicon as a radio detector is quite old, but the modern silicon varistor is essentially the outcome of microwave developments. As a result most silicon varistors are housed in either of the two standardized mountings shown in Figs. 13(a) and 13(b) which were originally

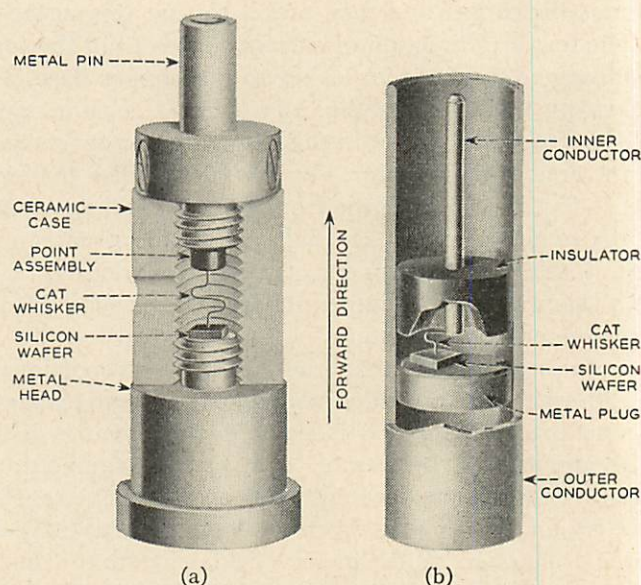


Fig. 13—Two types of silicon varistors originally designed for microwave applications.

designed to plug into microwave equipment. Fig. 13(a) is a ceramic case assembly first produced for use as a

mixer at 3,000 to 9,000 mc. Fig. 13(b) is a coaxial design produced for operation in the 24,000-mc region and also used at lower frequencies. In each of these units a small wafer of metallic silicon, generally about 50 mils square and 10 mils thick, is soldered to a brass pin. The "catwhisker," a wire of tungsten, platinum, phosphor bronze, and the like, from 3 to 15 mils in diameter, is soldered to another pin. During the process of manufacture these two pins are advanced until contact is made between the silicon wafer and the catwhisker.

Forward direction of current flow in this varistor is from the silicon to the catwhisker¹⁵ as shown by the arrow in Fig. 13(a).

In the forward direction the silicon varistor has the lowest dc resistance of any of the point contact type of varistors, the forward current at one volt being between 10 and 60 milliamperes. At zero bias its dynamic resistance is much lower than that of germanium and somewhat lower than for most 3/16-inch copper-oxide varistors. In the reverse direction the resistance (both dc and ac) reaches its maximum value at less than $\frac{1}{4}$ volt as shown in Fig. 2. For reverse voltages of the order of one to three volts the reverse current is quite low, but beyond this the reverse current increases quite fast so that reverse voltages must be limited to this order of magnitude to prevent damage to the unit.

In general, silicon varistors have not received the attention they deserve in the past, probably because of the fact that the cost of most commercial units includes an expensive microwave test which is not necessary if the unit is to be used at lower frequencies. In addition to their superior performance at microwaves, they are well suited for many lower frequency applications, particularly where wide frequency bands are to be covered and medium impedance levels are desired.

Germanium Varistors

While germanium varistors are the newest variety of point contact varistors, their production greatly exceeds that of silicon varistors. The basic structure of most commercial units (see Fig. 14(a)) is quite similar to silicon units except that the case is generally equipped with pigtail leads, allowing the units to be mounted in much the same manner as small 1-watt size resistors. As in the silicon varistor, one metal pin has a small wafer of metallic germanium soldered to it and another pin a "catwhisker" of tungsten, platinum, or the like, wire. One difference is that the forward direction¹⁶ of current flow is opposite to that of the silicon varistor, and is from

catwhisker to the germanium as shown by the arrow in Fig. 14(a).

In the forward direction, germanium varistors pass from 3 to 25 milliamperes at 1 volt. In the reverse directions, these varistors are unique in the high reverse voltage which they will withstand. The maximum dc resistance does not occur until the unit is biased 5 to 10 volts in the reverse direction. This maximum resistance is practical always over 100,000 ohms and frequently is one or more megohms.

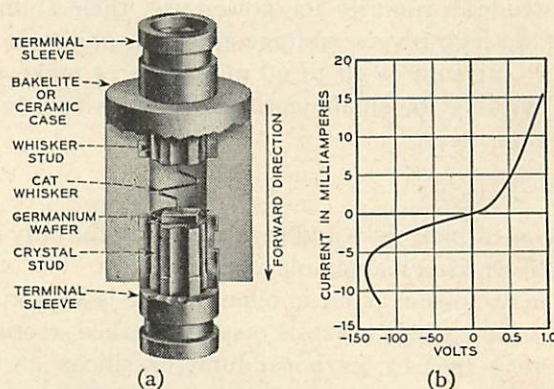


Fig. 14—Germanium varistor.

- (a) Cross section of one type of germanium varistor.
(b) Voltage-current characteristic of a germanium varistor.

In the reverse direction these varistors show the characteristic maximum voltage and negative-resistance region as discussed in connection with Fig. 1(a) and as shown in the volt-ampere characteristic in Fig. 14(b). Except for one special type to be mentioned later, in practically all commercial units, this maximum is greater than 75 volts and many units will withstand voltages of 150 volts and greater.

Almost every manufacturer of germanium varistors today offers several types, all of which are of the same construction and manufacture, differing only in the values of minimum forward current, maximum reverse current, and peak reverse current at which the units are tested. If one examines a tabulation of these values he is impressed by the lack of any apparent systematic classification. One wonders if many codes have not been established because of the failure of the design engineer to understand his own requirements and particularly that these dc requirements do not always completely specify the performance of the unit. Recently units have been made available which are selected for use as detectors at 40 Mc in a specified circuit. This code will undoubtedly meet the need for which it was designed, but it leaves unsolved the problem of the design engineer who requires a unit for use at a different frequency or in a different circuit.

In addition to the standard type of germanium varistor, a second distinctly different type is now available

¹⁵ This statement holds for varistors made from P-type silicon which probably includes all units in commercial production. Since both P- and N-type silicon can be prepared, it is possible to make a silicon varistor in which the direction of the forward current is reversed.

¹⁶ This direction is for N-type germanium of which most, if not all, commercial germanium varistors are made. As in the case of silicon, metallic germanium can be prepared in either the N- or P-type, so a germanium varistor can be made with the opposite direction of forward current.

for use at ultra-high frequencies. In this unit the forward characteristic curve is steeper than the usual type unit and the maximum peak inverse voltage is appreciably less, generally of the order of 10 volts. The frequency characteristic of these units is superior to the characteristics of the usual units, making possible their application up into the hundreds of megacycles.

The large portion of germanium varistors manufactured today are used in communication circuits for such purposes as final detectors, clippers and other limiters, clamp circuit (so-called dc reinsertion circuits), modulators, gating and switching circuits, and the like. While not intended primarily for power use, their ability to withstand high reverse voltage and their ability to pass forward currents of 40 to 60 milliamperes make them quite suitable for small rectifiers for bias supply and similar purposes.

Silicon Carbide

Silicon-carbide disks and rods are today the only symmetrical varistors available commercially. The statement may appear as an anomaly, as it is well known that silicon-carbide crystals display marked rectifying properties. In fact, carborundum, or silicon carbide, crystals were once extensively used as crystal detectors in radio telegraphy.

The present-day silicon-carbide varistor consists of silicon-carbide granules mixed with suitable binding material and fired to form a ceramic-like rod or disk. In this form the silicon-carbide crystals are essentially connected in series-parallel with random polarity and, as a result, all nonsymmetry in conduction is lost. Contacts to these rods or disks, which may vary from $\frac{1}{4}$ to 6 inches in diameter, are generally made by plating the opposite faces.

In general, the field of application of silicon carbide lies in the higher voltage range. The exponent n of equation (1) for silicon carbide has a value of from 3.5 up to as high as 7.0, but these values can only be obtained when the potential gradient within the varistor is at least 100 to 300 volts per inch. When the potential gradient falls below this order of magnitude, the value of the exponent is markedly reduced. This generally restricts the application of silicon carbide to voltages somewhat greater than used with other types of varistors.

The major field of application of silicon carbide is in protective devices, particularly lightning arrestors, click and thump reducers, and the like.

APPLICATION OF VARISTORS

In the application of varistors, the first step is to analyze the problem at hand in order to determine which of the properties of the proposed varistors will determine their operation in the proposed application. This step is important because properties which have little or no effect on the operation in one application may be of determining importance in another applica-

tion. To demonstrate this fact, in this section three applications will be discussed, each of which requires a different viewpoint. In power rectification one important problem is to prevent the destruction of the varistors due to internal power losses. In modulators, physical failure of the varistors is almost never a problem, but considerable attention must be paid to the magnitude of distortion products generated. In the compandor, successful operation depends on the uniformity of the slope of the forward characteristic.

Application of Varistors to Power Rectifiers

In power rectification one major problem is to keep internal losses low enough so that the varistor will not be damaged by overheating. Two different losses are present: (1) those due to the low series resistance during the forward portion of the cycles, and (2) those due to the leakage through the high reverse resistance during the reverse half of the cycle. The first is a function of the current through the varistor and decreases as the temperature rises, while the second is a function of the voltage across the varistor and increases as the temperature rises. As a result the total loss may either increase or decrease with temperature, depending on whether the varistor is operated with high reverse voltage and low forward current, or with low reverse voltage and high forward current.

The problem is to operate the varistor elements so that the heat generated within each element by these losses does not exceed the amount which the element can dissipate at the maximum allowable operating temperature. Forward losses are reduced by using larger area varistors or by operating varistors in parallel. Reverse losses are reduced by operating with more varistors in series. In addition to the limit imposed by losses in the reverse direction, it is sometimes also necessary to limit the reverse voltage to a value that will prevent the unit from failing due to voltage breakdown.

When operated at high ambient temperature the heat dissipation is reduced so ratings based on normal operating temperatures must be decreased.¹⁷ Similarly the power handling capacity may be greatly increased by forced ventilation or by intermittent operation. An example of the second type of service is the use of relatively small-size copper-oxide rectifiers to close circuit breakers. Here the rectifier is energized only occasionally and only for a short interval, hence the continuous duty rating of the rectifier can be greatly exceeded.

In practice, most power rectifiers are full-wave because of increased efficiency and better wave shape in the output. Fig. 15 shows two single-phase, full-wave rectifier circuits which externally are equivalent in all respects. Which of these circuits is used generally depends on the characteristics of the rectifying element. With vacuum tubes, except for high-voltage applica-

¹⁷ For example, see curve in bibliography reference (15).

tions, voltage in the reverse direction is not a limiting factor. Hence the center-tapped circuit of Fig. 15(a) is generally preferred because only two rectifying elements are required and because a single filament supply can be used. In a varistor rectifier, except for low-voltage applications, the reverse voltage requires more than one

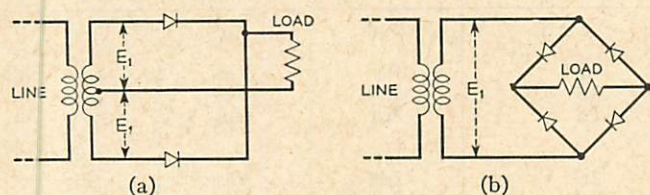


Fig. 15—Single-phase full-wave rectifier circuits.

varistor unit in series. Hence the bridge connection of Fig. 15(b) with its simpler transformer is generally preferred. In this circuit the total reverse voltage during each half of the cycle is impressed across one diagonally opposite pair of the varistors in the bridge. Similar rectifier circuits are available for polyphase operation.

Application of Varistors in Bridge- and Lattice-(Ring) Type Modulators

The extent that varistors have been utilized in bridge- and lattice-type modulators¹⁸ is probably little realized by engineers other than those directly connected with long-distance telephone service. The copper-oxide modulator was introduced in carrier telephone service about 1936 and very quickly supplanted the vacuum tube because of its simplicity, higher degree of stability, longer life, lower maintenance costs, absence of power drain during stand-by periods, and ability to act as a bilateral device.

Prior to the close of the second World War, all varistor modulators installed were of the copper-oxide type. These were initially installed in systems where the frequency translation was from voice frequency up to carrier frequencies of less than 100 kc. This range was then expanded into the hundreds of kilocycles, and finally in the coaxial system super-group modulators were developed which work at frequencies up to 2 mc.

Since the close of World War II, both silicon and germanium varistors have been used as modulators in carrier systems. While it is doubtful that it would be economical to replace copper-oxide modulators with silicon or germanium modulators in systems already installed or even already designed, it is probable that the

¹⁸ A modulator is a device which is used to translate a band of frequencies from one portion of the spectrum to another. This shift may be either upwards, as when transferring a message band from its original position to a new position in the spectrum, or downwards, as when the message band is restored to its original position. In the second case, the translation is sometimes referred to as demodulation, but since the processes are identical it is simpler here to group all such translations under the general term of modulation.

future trend will be away from copper-oxide modulators except for low-frequency applications, and possibly for applications in which a low noise level is necessary.

The outstanding problem in modulators is the reduction of undesired modulation products. If two signals, such as a signal S and a carrier C , are impressed on any nonlinear device an infinite number of new components whose frequencies are $NC \pm MS$ are generated. Here N and M are integers having any value including zero. One of these new products, generally $C+S$ or $C-S$, is the desired new frequency, while others represent extraneous products which must be eliminated by selective circuits or must be reduced to acceptable values by circuit design.

All of this infinite number of modulation products may be divided into four groups, namely:

$$N_e C \pm M_o S \quad (A)$$

$$N_o C \pm M_e S \quad (B)$$

$$N_e C \pm M_o S \quad (C)$$

$$N_o C \pm M_e S \quad (D)$$

in which N_e and M_e are any even integer, including zero, and N_o and M_o are any odd integer. The spectra of these four groups of modulation products are shown in Fig. 16.

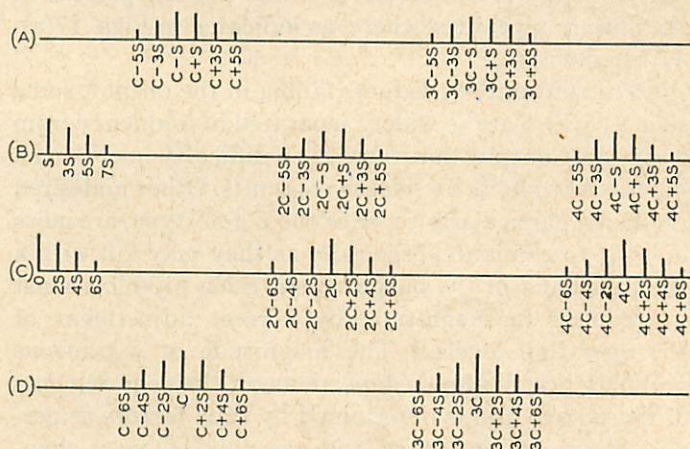


Fig. 16—Spectra of modulation products formed from a carrier of frequency C and a signal of frequency S .

When a single varistor or vacuum tube is used in a modulator circuit, all of these four groups of modulation products are present in the output. If, however, a multiple-unit modulator is used, certain of these groups can be eliminated from the output. Three circuits frequently used for this purpose are shown in Figs. 17(a), 17(b), and 17(c). Assuming perfect balance in the bridge-type modulator of Figs. 17(a) and 17(b), only the modulation products of groups (A) and (B) appear in the output. In the lattice- or ring-type modulator of Fig. 17(c) there is an additional degree of balance. Here only the

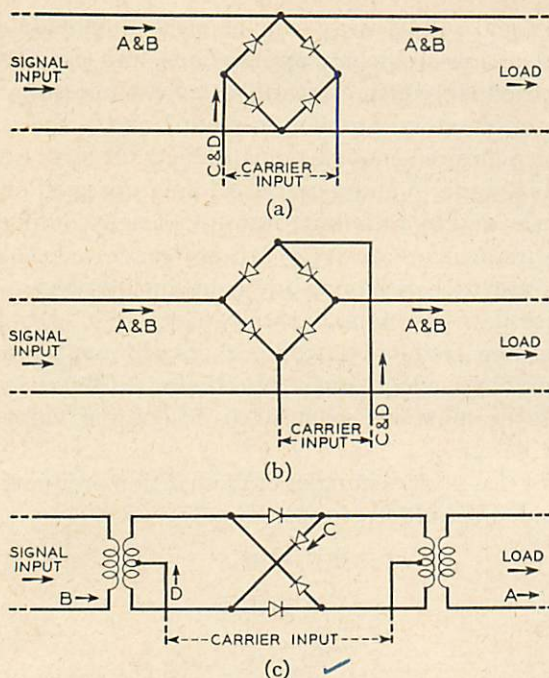


Fig. 17—Balanced modulator circuits. The letters A, B, C, and D in each circuit indicate the spectra (according to Fig. 16) appearing in various branches of these modulators.

products of group (A) appear in the output. In each of the modulators, the products which are not present in the output appear elsewhere, as indicated in Figs. 17(a), 17(b), and 17(c).

Of the unwanted products falling in the output, some such as $3C \pm S$ are so widely separated in frequency from the desired output that there is no difficulty in eliminating these products by selective circuits. Other undesired products, particularly those of the $C \pm 3S$ type, are more difficult to eliminate, especially as they may fall within the pass band of the output filter. Such products must be reduced in magnitude by correct adjustment of the operating levels.¹⁹ The magnitude of extraneous products permissible is dependent on the requirements of the system and is determined by such factors as permissible noise, distortion, and crosstalk between channels. In long-distance telephone circuits the limits imposed on single modulators may be quite severe, as these systems often contain several modulators in tandem, each of whose extraneous products contribute to the degradation of the circuit.

As an example of the order of magnitude of these various products, Table I indicates the worst value to be expected when using four Western Electric 3/16-inch copper-oxide varistors in a lattice-type circuit. In this table, it is assumed that the balance of the varistor suppresses carrier, and so forth, by only 25 db. This represents only a moderate degree of selection of the varistor elements and greater suppression can be obtained.

¹⁹ See bibliography reference (24).

TABLE I
MODULATION PRODUCTS IN OUTPUT OF LATTICE-TYPE
MODULATOR USING WESTERN ELECTRIC CO.
3/16-INCH COPPER-OXIDE VARISTORS

Carrier Input: 15 db above 1 milliwatt
Sideband Output: 10 db below 1 milliwatt

Product	Order of Modulation	Is Product Affected by Balance?	Amplitude of Product in db below (C-S)
$C \pm S$	2nd	No	0
S	1st	Yes	20
$2S$	2nd	Yes	40
$3S$	3rd	Yes	70
C	1st	Yes	0
$2C$	2nd	Yes	10
$3C$	3rd	Yes	5
$4C$	4th	Yes	13
$5C$	5th	Yes	8
$6C$	6th	Yes	15
$7C$	7th	Yes	10
$2C \pm S$	3rd	Yes	20
$3C \pm S$	4th	No	5
$4C \pm S$	5th	Yes	23
$5C \pm S$	6th	No	8
$6C \pm S$	7th	Yes	25
$7C \pm S$	8th	No	10
$C \pm 2S$	3rd	Yes	45
$C \pm 3S$	4th	No	50
$2C \pm 2S$	4th	Yes	50
Noise	10 db above thermal noise		

Note: Above values are probable worst values. Only a moderate degree of balance is assumed and those products affected by balance can be reduced to greater extent if the balance is improved.

The degree of balance obtained is inherently dependent on the effort used in selecting the individual varistors of the modulator assembly. With purely random selection one cannot expect better than 10-to-1 reduction.²⁰ With a reasonable degree of selection, reductions as high as 50 to 1 can be obtained. For special application, even higher reduction can be obtained, particularly if auxiliary balancing circuits may be used. Once the balance is obtained, it is quite stable, in marked contrast to the balance obtained when using balanced vacuum-tube modulators.

The maintenance of the balance in a modulator is a severe test of the stability of varistors. Either the varistors must show no aging, or the aging from unit to unit must be extremely uniform. The degree to which this balance can be maintained, without any adjustments, is illustrated in Fig. 18, which shows the results of two surveys on approximately 600 bridge-type modulators using 3/16-inch copper-oxide varistors located in toll centers in the eastern part of the United States. At the time of installation in 1938 to 1940 all modulators having a carrier leak greater than 33 db below the level of the carrier supply were rejected. The dotted curve

²⁰ These figures are for the ratio of carrier voltage across a bridge modulator to carrier voltage in output. Because of difference in impedance levels, the ratio of power at these points is greater.

shows the percentage of installed units having carrier leak equal to or greater than the value given on the abscissa. Carrier leak value ranging all the way from 33 to 63 db below the level of the carrier supply were obtained, with 50 per cent of the modulators having a carrier leak of 43.4 db below carrier level or less. During 1949 the second survey was made on these same units and the results are shown by the solid line. This survey showed that while some changes had occurred in the in-

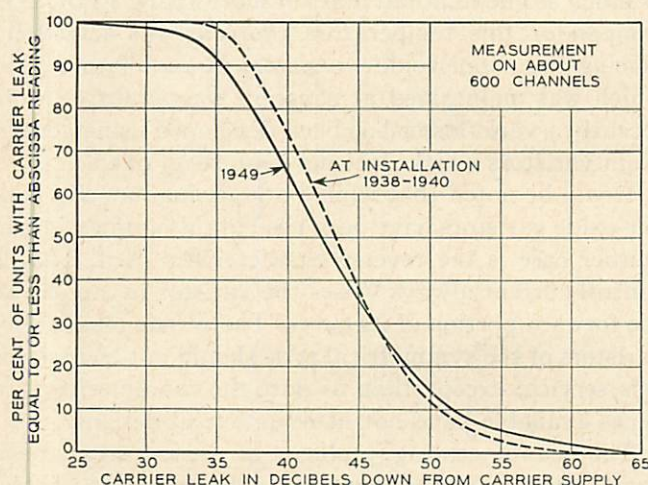


Fig. 18—Results of two surveys showing the stability of balance in copper oxide modulators.

dividual modulators, from a statistical viewpoint there has been little change in the group of modulators as a whole.

In a preceding section it was pointed out that the dynamic resistance of a copper-oxide varistor drops rapidly as the frequency is increased. This plus the shunting effect of the capacitance would indicate that copper-oxide modulators are limited to audio and perhaps the lower carrier frequencies. That this is not the case may be seen by experience on the type-L1 coaxial system. In this system a total of 60 message channels are assembled to form a super-group occupying the frequency space from 312 to 552 kc. Eight such super-groups are assembled, and then each is translated to its position on the coaxial line using a lattice modulator such as shown in Fig. 17(c).²¹ In each of these modulators, the input transformer has a ratio of 72 to 66 ohms, while the ratio of the output transformer is progressively reduced so that as the frequency is increased the varistor lattice operates into a lower and lower impedance. By this means it has been found possible to operate copper-oxide modulators to 2 mc with only the small increase in loss shown in Table II.

²¹ There is no modulator for super-group No. 2 as the line frequency of this super-group is the same as the frequency band in which the super-group is assembled.

Since the original design of the L1 system, two additional super-groups have been added at 2,172 to 2,408 kc and 2,552 to 2,788 kc. By the time this addition was made, silicon varistors were available and for these two higher-frequency super-group silicon varistors operating at impedance levels of about 400 ohms are now used.

Modulators are one application of varistors which in practice are relatively free from troubles due to ambient temperature variations, except where high degree of balance is desired. This is because the carrier voltage applied is sufficient to drive the varistor into that portion of the characteristic where temperature effects are of negligible magnitude.

TABLE II
SUPER-GROUP MODULATORS FOR TYPE-L1 CARRIER

Super-Group No.	Line Frequency kc	Carrier Frequency kc	Impedance Ratio of Output Trans.	Modulator Loss—db
1	68 to 308	620	75 to 72	6.5
2	312 to 552	—	—	—
3	564 to 804	1,116	46 to 72	6.7
4	812 to 1,052	1,364	46 to 72	6.8
5	1,060 to 1,300	1,612	33 to 72	7.2
6	1,308 to 1,548	1,860	33 to 72	7.3
7	1,556 to 1,796	2,108	25 to 72	7.6
8	1,804 to 2,044	2,356	25 to 72	8.0

Application of Varistors in Companders

In communication circuits the distance between repeater points is determined by the rate of attenuation of the medium, the maximum power available at the output of each repeater, and the noise level at the input of

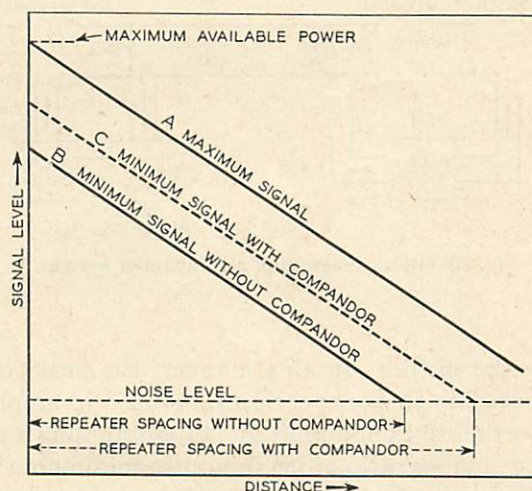


Fig. 19—Signal levels between two repeater stations showing the effect of a compander on repeater spacing.

each repeater. When the signal to be transmitted varies in amplitude, as it will in a commercial telephone circuit due not only to normal variations in amplitude present in speech but also to variation in level of differ-

ent talkers, the situation is as shown in Fig. 19. At the first repeater the output must be adjusted so the maximum signal does not exceed the maximum available power. The minimum signal is then attenuated according to curve *B* and the next repeater must be located before this signal falls below the noise level. If the ratio of maximum to minimum signal could be decreased so that the minimum signal is that shown in curve *C*, it would be possible to increase the distance between repeaters.

One way to accomplish this is to pass the signal at the transmitting end through a circuit which acts as a compressor. At the far end of the circuit the signal is passed through an expander which restores the signal to its original shape. This combination of a compressor followed by an expander has been termed a "comparator."

The comparator was first introduced to combat static on hf transoceanic radio circuits.²² Later it was applied to wire lines²³ in special locations where the improvement in noise and crosstalk was needed. More recently the comparator has been engineered as an integral part of new carrier telephone systems.

Fig. 20 shows a block diagram of one type of comparator. At the transmitting end the speech is passed through a variable pad or vario-losser whose loss is controlled by a dc current derived by rectifying the output of the signal. The time constant of the circuit is such that this dc current varies at syllabic rate, rather than following the instantaneous values of speech. When a loud signal is applied, the large dc control current effectively increases the attenuation of the vario-losser and

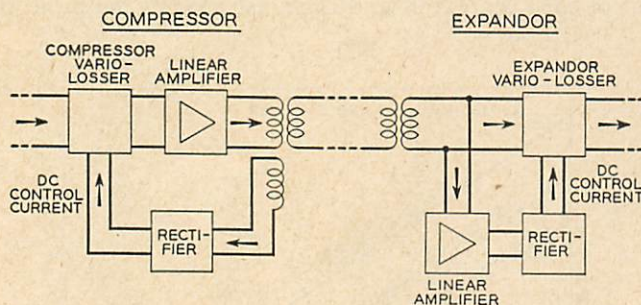


Fig. 20—Block diagram of a comparator system.

reduces the output. In this manner, the peaks of the slow variations in the speech are reduced in amplitude in proportion to their amplitude, thus obtaining a signal having a smaller ratio of maximum to minimum signal.

At the received end a portion of the incoming signal is rectified and another dc control current obtained. This control current is applied to a second vario-losser, which performs the reverse function of the vario-losser in the transmitting end restoring the signal to its original condition.

²² See bibliography reference (27).

²³ See bibliography reference (28).

The heart of the comparator is the two vario-lossers. These are passive networks composed of varistors and resistors. In this application the property of the varistor used is its ability to change its dynamic or ac resistance in accordance with variations of a dc bias. In selecting varistors for this application a much greater stress must be placed on uniformity than in most other applications, as the operation of the vario-losser at the receiving end must exactly complement that of the one at the transmitting end. Temperature variations are also important, particularly as the two ends of the circuit may be located as much as one hundred miles or more apart. In the first comparator this temperature problem was solved by placing the copper-oxide varistors in a miniature oven which was maintained at constant temperature. More recently a vario-losser has been developed using germanium varistors which does not require an oven.

It will be noted that while both germanium and copper-oxide varistors have been used in this application, in neither case is the reverse characteristic used. The dc control current always biases the varistor to a point on the forward portion of its curve. There is no reason why varistors of the symmetrical type should not be used for this service, except that to date the characteristics of types available have not fitted practical designs.

The manufacturing problem of vario-lossers for a comparator system requires a high degree of control of uniformity of the product, especially since it is desirable from an operating viewpoint that any expander vario-losser be suitable to operate with any compressor vario-losser. As an initial step the germanium varistors are classified in accordance with their dynamic resistance at two different dc biases. Following this, a vario-losser pad is made from the selected varistors and its transmission characteristic measured at several values of dc control current. In the case of the compressor vario-losser, an additional test for balance is required to insure against singing around the amplifier-rectifier-control circuit path.

To study the stability of germanium varistors in comparator service, eight vario-lossers were placed on life test in a circuit in which the dc control current was the maximum value encountered in service. At intervals an ac input was applied to each vario-losser and its output was measured. This life test was conducted for over 14,000 hours. During this period, variations in output were of a random nature, the greatest total variation being 0.5 db. Most of the units showed total variations not exceeding 0.3 db with at least half of this variation, probably due to variations in the measuring circuit.

OTHER APPLICATIONS

In addition to these three applications, there are many other uses for varistors, each of which has its own peculiar set of requirements. For protective circuits, such as the lightning arrestors in power distribution circuits or the click reducers connected across telephone operators' headsets, it is important that the varistor present a high

shunt impedance to the normal low voltages and instantaneously offer a low impedance path to any high-voltage surge. In some such applications ability to dissipate the energy in the surge is an important factor in the design, as illustrated by the use of large size silicon carbide disks in lightning arrestors.

Computers sometimes contain a large number of parallel circuits, each having a varistor normally biased in the reverse direction. By reversing the bias on one varistor so that it works on the forward portion of its characteristics, a gate is opened and a pulse is admitted to the circuit. In this application the dc resistance of the varistor in the reverse direction is often of major importance, as the total dc resistance of all varistors in parallel determines the impedance level for which the computer circuit may be designed. This impedance level in turn has a major influence on the total power consumption of the computer.

In conclusion, the writer hopes to have shown that all varistors, whether they be copper-oxide rectifiers, silicon carbide disks, crystal diodes, or the like, possess many common properties, and that the engineering application of varistors requires not only an understanding of these properties but also an appreciation of which of the properties play dominant roles in the application at hand.

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